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$\mathbf{D_{s0}^+(2317)}$ as an Iso-triplet Four-quark Meson and Production of Its Neutral and Doubly Charged Partners*

Kunihiko Terasaki
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
Institute for Theoretical Physics, Kanazawa University, Kanazawa 920-1192, Japan

By studying $D_{s0}^+(2317) \to D_s^+\pi^0$ and $D_{s0}^+(2317) \to D_s^{*+}\gamma$ decays, it is shown that assigning $D_{s0}^+(2317)$ to the iso-triplet four-quark meson $\hat{F}_I^+$ is favored. Productions of its partners $\hat{F}_I^0$ and $\hat{F}_I^{++}$ are also studied. As the result, it is concluded that they could be observed in $B_d^0 \to (D_s^+\pi^-)\bar{D}^0$ and $B_u^+ \to (D_s^+\pi^+)D^-$. Their iso-singlet partner $\hat{F}_0^+$ might have been observed in the radiative $B_{u(d)}^{+(0)} \to \bar{D}^{0(-)}D_s^{*+}\gamma$ decays by the BELLE collaboration.

I. INTRODUCTION

Inclusive e^+e^- annihilation experiments [1, 2] have observed a narrow (< 4.6 MeV [3]) scalar resonance [denoted by $D_{s0}^+(2317)$] in the $D_s^+\pi^0$ channel. However, no evidence for it has been observed in the $D_s^{*+}\gamma$ channel, so that a severe constraint [2],

$$R(D_{s0}^+(2317)) = \frac{\Gamma(D_{s0}^+(2317) \to D_s^{*+}\gamma)}{\Gamma(D_{s0}^+(2317) \to D_s^+\pi^0)} < 0.059, \tag{1}$$

has been provided. In addition, we here list the measured ratio of decay rates [3]

$$R(D_s^{*+})^{-1} = \frac{\Gamma(D_s^{*+} \to D_s^+\pi^0)}{\Gamma(D_s^{*+} \to D_s^{*+}\gamma)} = 0.062 \pm 0.008. \tag{2}$$

Eq. (2) implies that the isospin non-conserving interaction is much weaker than the electromagnetic interaction. Therefore, Eq. (1) means that the underlying interaction of the decay $D_{s0}^+(2317) \to D_s^+\pi^0$ is much stronger than the electromagnetic interaction, i.e., it is the ordinary strong interaction as is well known. In this case, $D_{s0}^+(2317)$ should be an iso-triplet meson which can be realized by a four-quark state.

To confirm the above conjecture, we shortly visit scalar four-quark mesons and discuss that charm-strange scalar four-quark mesons can be narrow, in **II**, and study their radiative decays and isospin non-conserving decays in **III**. Productions of charm-strange scalar mesons in e^+e^- annihilation and in hadronic B decays are investigated in **IV**. A brief summary is given in the final section.

II. CHARMED SCALAR FOUR-QUARK MESONS

Observed low lying scalar mesons [3], $a_0(980)$, $f_0(980)$, $K_0^*(800)$ and $f_0(600)$, can be well understood by the $[qq][\bar{q}\bar{q}]$ states, $\hat{\delta}^s \sim [ns][\bar{n}\bar{s}]_{I=1}$, $\hat{\sigma}^s \sim [ns][\bar{n}\bar{s}]_{I=0}$, $\hat{\kappa} \sim [ud][\bar{n}\bar{s}]$, $\hat{\sigma} \sim [ud][\bar{u}\bar{d}]$, $(n = u, d)$, which are dominantly of $\bar{3}_c \times 3_c$ of color $SU_c(3)$, as suggested long time ago [4] and supported at this workshop [5]. (However, for simplicity, a possible small mixing of $6_c \times \bar{6}_c$ is ignored in this talk.)

With this in mind, we replace one of light quarks in $[qq][\bar{q}\bar{q}]$ by the charm quark c. Then we have the charmed scalar $[cq][\bar{q}\bar{q}]$ mesons, $\hat{F}_I \sim [cn][\bar{n}\bar{s}]_{I=1}$, $\hat{F}_0^+ \sim [cn][\bar{n}\bar{s}]_{I=0}$, $\hat{D}^s \sim [cs][\bar{n}\bar{s}]$, $\hat{D} \sim [cn][\bar{u}\bar{d}]$ and $\hat{E}^0 \sim [cs][\bar{u}\bar{d}]$. However, we here study only $\hat{F}_I^{0,+,++}$ and $\hat{F}_0^+$. (For the other components, see Refs.[6, 7, 8].) When we assign [6] $D_{s0}^+(2317)$ to $\hat{F}_I^+$ as conjectured in **I**, one might wonder if it can be so narrow. However, its narrow width can be understood by a small rate for the dominant decay $\hat{F}_I^+ \to D_s^+\pi^0$ which is given by a small overlap of (color and spin) wavefunctions. Such a small overlap can be seen by decomposing a color-singlet scalar four-quark state of $\bar{3}_c \times 3_c$ into a sum of products of $\{q\bar{q}\}$ pairs. The coefficient of the product of two color- and spin-less $\{q\bar{q}\}$ pairs in the decomposition provides the overlap under consideration. Therefore, the parameters describing the overlaps between a charm-strange scalar four-quark meson and two pseudoscalar mesons, for example, $\hat{F}_I^+$ (or $\hat{F}_0^+$) and $D_s^+\pi^0$ (or $D_s^+\eta$) is given by $|\beta_0|^2 = 1/12$,

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and the corresponding one between $\hat{F}_I^+$ (or $\hat{F}_0^+$) and $D_s^{*+}\rho^0$ (or ω, ϕ, ψ) is provided by $|\beta_1|^2 = 1/4$. (However, in the case of the conventional mesons, the corresponding overlap is unity, because their color and spin configuration is unique.) For more details, see Refs. [7, 9, 10]. To see numerically that $\hat{F}_I^+$ is narrow, we use a hard pion technique in the infinite momentum frame [11]. In this approximation, the amplitude for two body decay $A(\mathbf{p}) \to B(\mathbf{q})\pi(\mathbf{k})$ is given by

$$M(A \to B\pi) \simeq \left(\frac{m_A^2 - m_B^2}{f_\pi}\right)\langle B|A_{\bar{\pi}}|A\rangle, \tag{3}$$

where the asymptotic matrix element $\langle B|A_{\bar{\pi}}|A\rangle$ has been evaluated in the infinite momentum frame. Then, by assigning $a_0(980)$ to $\hat{\delta}^s$ and using $\Gamma(a_0(980) \to \eta\pi)_{\rm exp} \simeq 60$ MeV from the measured peak width [3] as the input data, a rather small rate $\Gamma(\hat{F}_I^+ \to D_s^+\pi^0)_{SU_f(4)} \simeq 8$ MeV can be obtained, where the η-η' mixing with the mixing angle $\theta_P \simeq -20^\circ$ has been taken. Because the spatial wavefunction overlap is in the $SU_f(4)$ symmetry limit at this stage, however, it is expected that the amplitude is overestimated by about $20 - 30$ %. It can be seen [7] by comparing the measured rates for the $D^* \to D\pi$ decays with the estimated ones in which the measured $\Gamma(\rho \to \pi\pi)_{\rm exp} = 149.4 \pm 1.0$ MeV [3] is adopted as the input data. Taking account for the above symmetry breaking, we can get $\Gamma(\hat{F}_I^+ \to D_s^+\pi^0) \sim 3 - 5$ MeV. This leads to a sufficiently narrow width of $\hat{F}_I^+ = D_{s0}^+(2317)$ [7, 10].

III. RADIATIVE DECAYS AND ISOSPIN NON-CONSERVING DECAYS

Since it has been known that the vector meson dominance (VMD) with the ideal ω-ϕ mixing and the flavor $SU_f(3)$ symmetry for the strong vertices works fairly well in the radiative decays of light vector mesons [12], we will extend it to the system containing charm quark(s) below. Under the VMD, the amplitude $A(V \to P\gamma)$ can be approximated by

$$A(V \to P\gamma) \simeq \sum_{V'=\rho^0,\,\omega,\,\phi,\,\psi}\left[\frac{X_{V'}(0)}{m_{V'}^2}\right]A(V \to PV'), \tag{4}$$

where $X_V(0)$ is the γV coupling strength on the photon mass-shell. X_V is dependent on photon-momentum-square [12], and the values of $X_V(0)$ have been estimated from the analyses in photoproductions of vector mesons on various nuclei [13]. The results are $X_\rho(0) = 0.033 \pm 0.003$ GeV^2, $X_\omega(0) = 0.011 \pm 0.001$ GeV^2, $X_\phi(0) = -0.018 \pm 0.004$ GeV^2 and $X_\psi(0) \sim 0.054$ GeV^2, where the last one has been obtained from $d\sigma(\gamma N \to \psi N)/dt|_{t=0} \simeq 20$ nb/GeV^2 and $\sigma_T(\psi N) = 3.5 \pm 0.8$ mb [14] for the ψN total cross section. (N denotes a nucleon). The VPV' coupling strength can be estimated as

$$|A(\omega \to \pi^0\rho^0)| \simeq 18\,\mathrm{GeV}^{-1}, \tag{5}$$

from the measured rate [3] $\Gamma(\omega \to \pi^0\gamma)_{\rm exp} = 0.757 \pm 0.024$ MeV by putting $V = \omega$, $P = \pi^0$ and $V' = \rho^0$ in Eq. (4) and by inserting the above $X_\rho(0)$ into it, because the $\omega \to \pi^0\gamma$ amplitude is dominated by the ρ^0 pole. The OZI-rule allowed poles for the amplitude $A(D^{*+} \to D^+\gamma)$ are given by the ρ^0, ω and ψ mesons. The relevant $SU_f(4)$ relation $-2A(D^{*+} \to D^+\rho^0) = 2A(D^{*+} \to D^+\omega) = \sqrt{2}A(D^{*+} \to D^+\psi) = \cdots = A(\omega \to \pi^0\rho^0)$ with Eq. (5) leads to $\Gamma(D^{*+} \to D^+\gamma)_{SU_f(4)} \simeq 2.4$ keV. By comparing the above rate with the measured one [3] $\Gamma(D^{*+} \to D^+\gamma)_{\rm exp} \simeq 1.5$ keV (with ~ 50 % errors), it is seen [7] that (the VMD with) the $SU_f(4)$ symmetry (of spatial wavefunction overlap) again overestimates the rate by ~ 50 %, as in **II**.

Now we study radiative decays of charm-strange mesons. The amplitude for $D_s^{*+} \to D_s^+\gamma$ is dominated by ϕ and ψ poles. Taking the $SU_f(4)$ symmetry relation, $\sqrt{2}A(D_s^{*+} \to D_s^+\phi) = \sqrt{2}A(D_s^{*+} \to D_s^+\psi) = \cdots = A(\omega \to \pi^0\rho^0)$, and Eq. (5), we can obtain the rate for the $D_s^{*+} \to D_s^+\gamma$ listed in Table I. For radiative decays of scalar mesons, we consider typical three cases, (i) $S = D_{s0}^{*+} \sim \{c\bar{s}\}$, (ii) $S = \hat{F}_0^+$ and (iii) $S = \hat{F}_I^+$. Under the VMD, the amplitude is obtained by replacing (V, P) in Eq. (4) in terms of (S, V). In the case (i), the amplitude $A(D_{s0}^{*+} \to D_s^{*+}\gamma)$ is dominated by the ϕ and ψ poles. Using the $SU_f(4)$ relation, $2A(D_{s0}^{*+} \to D_s^{*+}\phi) = 2A(D_{s0}^{*+} \to D_s^{*+}\psi) = \cdots = A(\chi_{c0} \to \psi\psi)$, and the input data, $\Gamma(\chi_{c0} \to \psi\gamma)_{\rm exp} = 135 \pm 15$ keV [3], we have the rate for the decay $D_{s0}^{*+} \to D_s^{*+}\gamma$ listed in Table I. The amplitudes $A(\hat{F}_0^+ \to D_s^{*+}\gamma)$ and $A(\hat{F}_I^+ \to D_s^{*+}\gamma)$ in the cases (ii) and (iii) are dominated by the ω pole and the ρ^0 pole, respectively. Taking the $SU_f(4)$ relation, $A(\hat{F}_0^+ \to D_s^{*+}\omega) = A(\hat{F}_I^+ \to D_s^{*+}\rho^0) = \cdots = A(\phi \to \hat{\delta}^{s0}\rho^0)\beta_1$, with the overlap parameter β_1 given in **II** and the input data, $\Gamma(\phi \to a_0(980)\gamma)_{\rm exp} = 0.32 \pm 0.03$ keV [3], we have the rates for radiative decays of charm-strange mesons listed in Table I, where the spatial wavefunction overlap is still

Table I. Radiative decays of charm-strange mesons with the spatial wavefunction overlap in the $SU_f(4)$ symmetry. The parameter β_1 which provides the overlap of color and spin wavefunctions is given in the text. The input data are taken from Ref. [3].

Decay	Pole(s)	β_1	Input Data (keV)	$\Gamma_{SU_f(4)}$ (keV)
$D_s^{*+} \to D_s^+\gamma$	ϕ, ψ	1	$\Gamma(\omega \to \pi^0\gamma)_{\rm exp}\ = 757 \pm 24$	0.8
$\hat{F}_I^+\ \to D_s^{*+}\gamma$	ρ^0	1/4	$\Gamma(\phi\ \to a_0\gamma)_{\rm exp}\ = 0.32 \pm 0.03$	45
$\hat{F}_0^+\ \to D_s^{*+}\gamma$	ω	1/4	$\Gamma(\phi\ \to a_0\gamma)_{\rm exp}\ = 0.32 \pm 0.03$	4.7
$D_{s0}^{*+} \to D_s^{*+}\gamma$	ϕ, ψ	1	$\Gamma(\chi_{c0} \to \psi\gamma)_{\rm exp} = 135 \pm 15$	35

in the $SU_f(4)$ symmetry limit. Then, the ratio of the rate $\Gamma(\hat{F}_I^+ \to D_s^{*+}\gamma)_{SU_f(4)}$ in Table I to $\Gamma(\hat{F}_I^+ \to D_s^+\pi^0)_{SU_f(4)}$ estimated in **II**,

$$\frac{\Gamma(\hat{F}_I^+ \to D_s^{*+}\gamma)_{SU_f(4)}}{\Gamma(\hat{F}_I^+ \to D_s^+\pi^0)_{SU_f(4)}} \sim 0.005, \tag{6}$$

satisfies well the constraint Eq. (1).

Isospin non-conserving decays are now in order. The amplitude for the $D_s^{*+} \to D_s^+\pi^0$ decay can be obtained by putting $A = D_s^{*+}$ and $B = D_s^+$ in Eq. (3). Here we assume [15] that the isospin non-conservation in decays of charm-strange mesons is caused by the η-π^0 mixing whose mixing parameter ϵ has been estimated to be [16]

$$\epsilon = 0.0105 \pm 0.0013. \tag{7}$$

It is very small and of the order of the fine structure constant α. This implies that the isospin non-conserving interaction is much weaker than the electromagnetic one. The $SU_f(4)$ symmetry of asymptotic matrix elements and the η-η' mixing lead to $2\langle D_s^+|A_{\pi^0}|D_s^{*+}\rangle = -\epsilon \sin\Theta \cdot \langle \pi^+|A_{\pi^+}|\rho^0\rangle$, where $\Theta \simeq 35^\circ$ for the usual η-η' mixing angle $\theta_P = -20^\circ$. The size of $\langle \pi^+|A_{\pi^+}|\rho^0\rangle$ can be estimated to be $|\langle \pi^+|A_{\pi^+}|\rho^0\rangle| \simeq 1.0$ [11] from the measured rate [3] $\Gamma(\rho \to \pi\pi)_{\rm exp} = 149.4 \pm 1.0$ MeV. In this way, we are lead to $\Gamma(D_s^{*+} \to D_s^+\pi^0)_{SU_f(4)} \simeq 0.05$ keV. Comparing this result with $\Gamma(D_s^{*+} \to D_s^+\gamma)_{SU_f(4)}$ in Table I, we obtain $R(D_s^{*+})^{-1} \simeq 0.06$. This is much smaller than unity, as conjectured in **I**, and reproduces well the measurement Eq. (2). Therefore, the present approach seems to be reliable.

With this in mind, we consider two cases of the isospin non-conserving decays of scalar mesons, (i) $S^+ = D_{s0}^{*+}$ and (ii) $S^+ = \hat{F}_0^+$. The amplitude for the $S^+ \to D_s^+\pi^0$ decay is obtained by putting $A = S^+$, $B = D_s^+$ and $\pi = \pi^0$ in Eq. (3). Since this decay is assumed to proceed through the η-π^0 mixing as discussed above, we replace the matrix elements, $\langle D_s^+|A_{\pi^0}|D_{s0}^{*+}\rangle$ and $\langle D_s^+|A_{\pi^0}|\hat{F}_0^+\rangle$, by the OZI-rule allowed $-\epsilon \sin\Theta \cdot \langle D_s^+|A_{\eta^s}|D_s^{*+}\rangle$ and $\epsilon\cos\Theta \cdot \langle D_s^+|A_{\eta^n}|\hat{F}_0^+\rangle$, respectively. The $SU_f(4)$ relations of asymptotic matrix elements are $\langle D_s^+|A_{\eta^s}|D_s^{*+}\rangle = \langle K^+|A_{\pi^+}|K_0^{*0}(1430)\rangle$ in the case (i) and $2\langle D_s^+|A_{\eta^n}|\hat{F}_0^+\rangle = \langle \pi^+|A_{\eta^s}|\hat{\delta}^{s+}\rangle\beta_0$ in the case (ii). The size of the former is estimated to be $|\langle K^+|A_{\pi^+}|K_0^{*0}(1430)\rangle| \simeq 0.29$ from the experimental data [3], $\Gamma(K_0^*(1430) \to K\pi)_{\rm exp} = 270 \pm 24$ MeV, and the isospin $SU_I(2)$ symmetry, where it has been assumed that $K_0^{*0}(1430)$ is the conventional ${}^3P_0\,\{d\bar{s}\}$ state [3]. The latter has already been obtained as $|\langle \pi^+|A_{\eta^s}|\hat{\delta}^{s+}\rangle| = \sqrt{1/2}|\langle \eta^s|A_{\pi^-}|\hat{\delta}^{s+}\rangle| \sim 0.6$ in **II**. Using the above results on the asymptotic matrix elements, the value of ϵ in Eq. (7) and $\theta_P = -20^\circ$, we have the rates for the isospin non-conserving decays, $\Gamma(D_{s0}^{*+} \to D_s^+\pi^0)_{SU_f(4)} \simeq \Gamma(\hat{F}_0^+ \to D_s^+\pi^0)_{SU_f(4)} \simeq 0.6$ keV. These results are much smaller than the rates for the radiative decays of the charm-strange scalar mesons listed in Table I, as conjectured in **I**. Eventually, the ratios of decay rates under consideration can be obtained as (i) $R(\hat{D}_{s0}^{*+}) \simeq 60$, (ii) $R(\hat{F}_0^+) \simeq 7$ and (iii) $R(\hat{F}_I^+) \simeq 0.005$ in Eq. (6). In this way, it is seen that the experimental constraint Eq. (1) can be satisfied only in the case (iii). (For more details, see Refs. [7, 10]) Its assignment to an iso-singlet DK molecule [17] has already been rejected [18] because it leads to $R(\{DK\}) \gg R(D_{s0}^+(2317))_{\rm exp}$ as in (ii). Thus we conclude that assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+$ is favored by the experiments while its assignment to the $I = 0$ state, the conventional scalar D_{s0}^{*+} or the scalar four-quark $\hat{F}_0^+$ (or the DK molecule), is not favored.

IV. PRODUCTION OF CHARM-STRANGE SCALAR MESONS

Although assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+$ is favored by experiments as seen above, its neutral and doubly charged partners, $\hat{F}_I^0$ and $\hat{F}_I^{++}$, have not yet been observed by inclusive e^+e^- annihilation experiment [19]. Therefore, we now study productions of charm-strange scalar four-quark mesons ($\hat{F}_I^{++,+,0}$ and $\hat{F}_0^+$). To this aim, we consider their

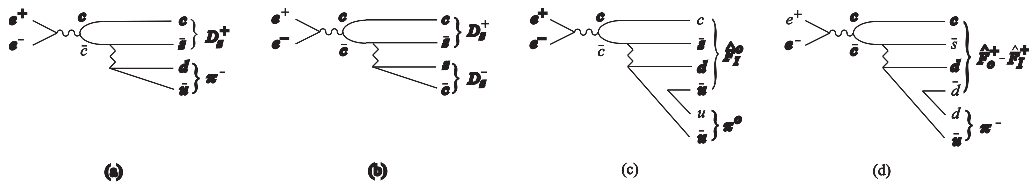

Fig. 1. Productions of charm-strange scalar mesons through $e^+e^- \to c\bar{c}$ within the minimal $q\bar{q}$-pair creation. (a) and (b) describe productions of $D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, etc. and $D_s^+D_s^-$, $D_s^{*+}D_s^-$, $D_s^+D_s^{*-}$, etc., respectively. Productions of $\hat{F}_I^0\pi^0$ and $(\hat{F}_0^+,\,\hat{F}_I^+)\pi^-$ are given by (c) and (d), respectively.

production through weak interactions, as a possible candidate, because OZI-rule violating creations of multiple $q\bar{q}$-pairs and their recombinations into four-quark meson states are expected to be strongly suppressed at high energies [9]. We, first, recall the so-called BSW Hamiltonian [20] as the effective weak Hamiltonian,

$$H_w^{\rm BSW} \propto a_1Q_1 + a_2Q_2 + \cdots + H_w' + h.c., \tag{8}$$

where Q_1 and Q_2 are four-quark operators given by products of neutral and charged currents, respectively, and provide amplitudes for color suppressed and color favored decays, respectively, under the factorization prescription. The extra term H_w' is automatically induced when the BSW Hamiltonian is obtained. It is given by a sum of products of colored currents and provides a non-factorizable amplitude, so that it is usually taken away. However, in this talk, it is left intact [21, 22] because it can play an important role in production of charm-strange scalar four-quark mesons.

Next, we draw quark-line diagrams within the minimal $q\bar{q}$-pair creation, because multiple $q\bar{q}$-pair creation is expected to be suppressed due to the OZI rule. In this approximation, the quark-line diagrams related to production of charm-strange scalar four-quark mesons in $e^+e^- \to c\bar{c}$ annihilation are given in Fig. 1. Because there is no diagram to describe production of $\hat{F}_I^{++}$ in this approximation, as seen in Fig. 1, it is understood why the $e^+e^- \to c\bar{c}$ experiment [19] found no evidence for it. Productions of $\hat{F}_I^0$, $\hat{F}_I^+$ and $\hat{F}_0^+$ mesons are described by Figs. 1(c) and (d). The diagrams Figs. 1(a) and (b) in which the weak vertices are given by the color favored spectator diagrams describe productions of $D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, etc. and $D_s^+D_s^-$, $D_s^+D_s^{*-}$, $D_s^{*+}D_s^-$, etc., respectively. By the way, it is known that color favored spectator decays are much stronger than color mismatched decays under the factorization prescription (i.e., $|a_1/a_2|^2 \simeq 6.8\times10^{-3}$ at the scale of charm mass [23]). In addition, non-factorizable contributions are actually small in hadronic weak decays of B mesons [21], and they will be much smaller at higher energies. As seen in Fig. 1, productions of $\hat{F}_I^{+,0}$ and $\hat{F}_0^+$ involve rearrangements of colors and their amplitudes are non-factorizable, so that they will be much more strongly suppressed than the color favored processes. Therefore, it is not very easy to extract the $\hat{F}_I^0 \to D_s^+\pi^-$ signals in *inclusive* $e^+e^- \to c\bar{c}$ experiments. In the case of $\hat{F}_I^+$, however, one does not need to worry about large numbers of background events from Figs. 1(a) and (b) because its main decay is $\hat{F}_I^+ \to D_s^+\pi^0$. Nevertheless, its evidence has not been observed in the radiative channel, because its decay into $D_s^{*+}\gamma$ is strongly suppressed as seen in **III**. As for $\hat{F}_0^+$, it can decay much more strongly into $D_s^{*+}\gamma$ than $D_s^+\pi^0$ as seen in **III**, although its production is depicted by the same diagram Fig. 1(d) as the production of $\hat{F}_I^+$. Therefore, reconstruction of $\hat{F}_0^+ \to D_s^{*+}\gamma$ might be suspected to be efficient to search for $\hat{F}_0^+$. However, very large numbers of D_s^{*+} and γ (from $D_s^{*-} \to D_s^-\gamma$) produced through the spectator diagrams Figs. 1(a) and (b) (and in $e^+e^- \to c\bar{c} \to D_s^{(*)+}D_s^{(*)-}$, etc. without weak interactions) obscure the above signal $D_s^{*+}\gamma$. In this way, it will be understood that whether each of charm-strange scalar mesons can be observed or not depends on its production mechanism, and, therefore, it seems that no evidence for $\hat{F}_I^0$ and $\hat{F}_I^{++}$ in inclusive $e^+e^- \to c\bar{c}$ annihilation experiments does not necessarily imply their non-existence.

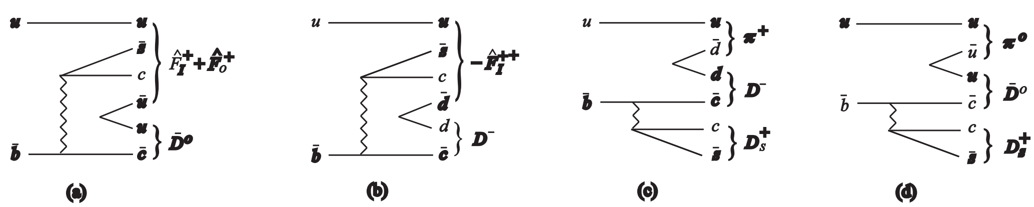

Fig. 2. Productions of charm-strange scalar mesons in weak decays of B_u meson. (a) describes a production of $\hat{F}_I^+$ and $\hat{F}_0^+$ with $\bar{D}^0$ (or $\bar{D}^{*0}$), (b) a production of $\hat{F}_I^{++}$ with D^- (or D^{*-}), and (c) and (d) productions of $D_s^+\pi^+$ with D^- and $D_s^+\pi^0$ with $\bar{D}^0$, respectively.

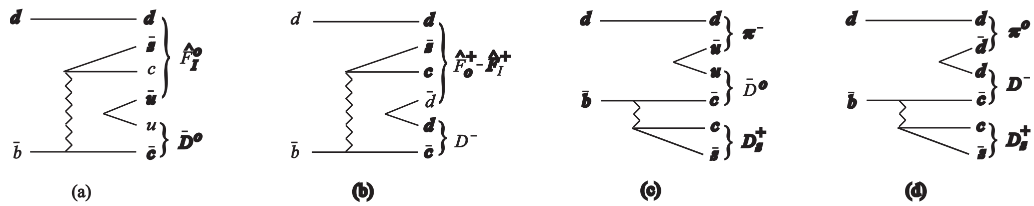

Fig. 3. Productions of charm-strange scalar mesons in weak decays of B_d meson. (a) describes a production of $\hat{F}_I^0$ with $\bar{D}^0$ (or $\bar{D}^{*0}$), (b) a production of $\hat{F}_I^+$ and $\hat{F}_0^+$ with D^- (or D^{*-}). (c) and (d) provide productions of $D_s^+\pi^-$ with $\bar{D}^0$ and $D_s^+\pi^0$ with D^-, respectively.

Because it is difficult to observe $\hat{F}_I^{++}$, $\hat{F}_I^0$ and $\hat{F}_0^+$ in inclusive $e^+e^- \to c\bar{c}$ experiments as seen above, we now study productions of charm-strange scalar four-quark mesons in B decays. For this purpose, we again draw quark-line diagrams describing their productions within the minimal $q\bar{q}$-pair creation. As expected in the quark-line diagrams of Figs. 2 and 3, resonance peaks which are approximately degenerate with $D_{s0}^+(2317)$ have been observed in the following hadronic weak decays of B mesons: $B_u^+ \to \bar{D}^0\tilde{D}_{s0}^+(2317)[D_s^+\pi^0, D_s^{*+}\gamma]$ and $B_d^0 \to D^-\tilde{D}_{s0}^+(2317)[D_s^+\pi^0, D_s^{*+}\gamma]$ in the BELLE experiment [24], and $B_u^+ \to \bar{D}^0(\text{or}\,\bar{D}^{*0})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ and $B_d^0 \to D^-(\text{or}\,D^{*-})\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ in the BABAR experiment [25]. It should be noted that indications of new resonances have been observed in the $D_s^{*+}\gamma$ channel. It is quite different from the case of inclusive $e^+e^- \to c\bar{c}$. Therefore, the new resonances have been denoted by $\tilde{D}_{s0}^+(2317)$[observed channel(s)] to distinguish them from the previous $D_{s0}^+(2317)$. Because Figs. 2(a) and 3(b) involve both $\hat{F}_I^+$ and $\hat{F}_0^+$ and their main decays are quite different from each other, the new resonance can be assigned to $\hat{F}_I^+$ when it is observed in the $D_s^+\pi^0$ channel, while it might be assigned to $\hat{F}_0^+$ when it is observed in the $D_s^{*+}\gamma$ channel. Observations of $\hat{F}_I^{++}$ and $\hat{F}_I^0$ are expected in the process $B_u^+ \to D^-(\text{or}\,D^{*-})\hat{F}_I^{++}[D_s^+\pi^+]$ as depicted in Fig. 2(b), and in the process $B_d^0 \to \bar{D}^0\hat{F}_I^0[D_s^+\pi^-]$ as depicted in Fig. 3(a), respectively. Because the diagrams Figs. 2(a), 2(b), 3(a) and 3(b) are of the same type, rates for production of $\hat{F}_I^{++}$ and $\hat{F}_I^0$ are expected to be not very far from that for $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$, i.e.,

$$B(B_u^+ \to D^-(\text{or}\,D^{*-})\hat{F}_I^{++}[D_s^+\pi^+]) \sim B(B_d^0 \to \bar{D}^0\,(\text{or}\,\bar{D}^{*0})\hat{F}_I^0[D_s^+\pi^-])$$
$$\sim B(B \to \bar{D}\,(\text{or}\,\bar{D}^*)\tilde{D}_{s0}^+(2317)[D_s^+\pi^0])_{\text{exp}} \sim 10^{-3}. \tag{9}$$

Therefore, $\hat{F}_I^{++}$ and $\hat{F}_I^0$ could be observed in $B \to \bar{D}(\text{or}\,\bar{D}^*)D_s^+\pi$ decays.

V. SUMMARY

By studying the $D_{s0}^+(2317) \to D_s^+\pi^0$ and $D_{s0}^+(2317) \to D_s^{*+}\gamma$ decays, we have seen that assigning $D_{s0}^+(2317)$ to $\hat{F}_I^+$ is favored by experiments. To search for its partners $\hat{F}_I^0$ and $\hat{F}_I^{++}$, we have investigated productions of these four-quark mesons through hadronic weak interactions. As the results, we have found that detecting them in inclusive $e^+e^- \to c\bar{c}$ is likely quite difficult, although $D_{s0}^+(2317)$ itself has already been observed. Taking these points into consideration, we have estimated the branching fractions for decays of B mesons producing $\hat{F}_I^{++}$ and $\hat{F}_I^0$ as $B(B_u^+ \to D^-\hat{F}_I^{++}) \sim B(B_d^0 \to \bar{D}^0\hat{F}_I^0) \sim 10^{-3}$. As for observation of $\hat{F}_I^+$ and $\hat{F}_0^+$, we conclude that they could have been observed as resonances with approximately equal masses in two different channels, $D_s^+\pi^0$ and $D_s^{*+}\gamma$, as the BELLE collaboration observed.

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